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14. ABSTRACT
Our investigation consists of three inter-related thrusts: traffic modeling and analysis, network control, and information assurance in wireline and wireless networks. We model multi-scale behavior in network systems, where traffic and system behavior can be highly correlated over multiple time scales (e.g., LRD). We investigate the causes of LRD traffic in network systems, which may result from traffic correlation, protocol behavior (e.g., retransmissions), and network congestion; and statistically analyzed the properties of LRD traffic from empirical

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Final Report: Stochastic Control of Multi-Scale Networks: Modeling, Analysis and Algorithms

ABSTRACT

Our investigation consists of three inter-related thrusts: traffic modeling and analysis, network control, and information assurance in wireline and wireless networks. We model multi-scale behavior in network systems, where traffic and system behavior can be highly correlated over multiple time scales (e.g., LRD). We investigate the causes of LRD traffic in network systems, which may result from traffic correlation, protocol behavior (e.g., retransmissions), and network congestion; and statistically analyzed the properties of LRD traffic from empirical data sets. We develop a unifying theory for network control that exploits the interactions across network functionalities, operates at appropriate time-scales, and is effective in the presence of LRD. We formulate optimization and distributed control problems for providing network services, and study the impact of LRD traffic on network control, performance, and security. We also develop an integrative approach that combines the LRD modeling and network control to obtain non-parametric or semi-parametric techniques for the distributed detection of information flow and flow changes needed for preventing security attacks. We characterize flow detectability as a function of flow rate, delay and memory constraints, and developed distributed detection schemes that guarantee vanishingly low detection error probabilities.

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(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
05/07/2012 39.00	Eytan Modiano, Lizhong Zheng, Krishna Jagannathan. On the Role of Queue Length Information inNetwork Control, IEEE Transactions in Information Theory, (12 2011): 0. doi:
08/18/2013 74.00	P. R Kumar, Hemant Kowshik. Optimal Computation of Symmetric Boolean Functions in Collocated Networks, IEEE Journal on Selected Areas in Communications, (04 2013): 0. doi: 10.1109/JSAC.2013.130403
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IEEE Transactions on Information Theory, (08 2010): 0. doi: 10.1109/TIT.2010.2050932

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09/05/2013 25.00 B. Xi,, K.M. Tan, C. Liu. Logarithmic Transformation Based Gamma Random Number Generators,
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Advances in Applied Probability, (09 2014): 0. doi:

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10/13/2014 65.00 Jin-Ghoo Choi, Changhee Joo, Junshan Zhang, Ness B. Shroff. Distributed Link Scheduling Under SINR Model in Multihop Wireless Networks ,
IEEE/ACM Trans. on Networking, (08 2014): 1204. doi:

10/13/2014 66.00 Changhee Joo, Ness B. Shroff. On the Delay Performance of In-Network Aggregation in Lossy Wireless Sensor Networks ,
IEEE/ACM Trans. on Networking, (04 2014): 662. doi:

10/14/2014 68.00 P. R. Kumar, Kyoung-Dae Kim. A Real-Time Middleware for Networked Control Systems and Application to an Unstable System,
IEEE Transactions on Control Systems Technology, (09 2013): 1898. doi:

10/14/2014 69.00 Kyoung-Dae Kim, P.R. Kumar. An Overview and Some Challenges of Cyber-Physical Systems,
Journal of the Indian Institute of Science, (07 2013): 341. doi:

10/14/2014 71.00 Kyoung-Dae Kim, P. R. Kumar. An MPC-based Approach to Provable System-wide Safety and Liveness of Autonomous Ground Traffic,
IEEE Transactions on Automatic Control, (08 2014): 0. doi:

10/14/2014	72.00	Jonathan Ponniah, Yih-Chun Hu, P. R. Kumar. A System-Theoretic Clean Slate Approach to Provably Secure Ad Hoc Wireless Networking, IEEE Transactions on Control of Network Systems, (10 2014): 0. doi:

TOTAL: **95**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
09/05/2013	95.00	Shengbo Chen, Prasun Sinha, Ness B. Shroff, Changhee Joo. A Simple Asymptotically Optimal Joint Energy Allocation and Routing Scheme in Rechargeable Sensor Networks, , (05 2013): 0. doi:

TOTAL: **1**

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(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
08/25/2012 88.00	I-Hong Hou, P. R. Kumar, . A Survey of Recent Results on Real-Time Wireless Networking, Proceedings of Real-time Wireless for Industrial Applications. 11-APR-10, . : ,
08/29/2011 41.00	Kyoung-Dae Kim, P. R. Kumar. The Importance, Design and Implementation of a Middleware for Networked Control Systems., Lecture Notes in Control and Information Sciences, Number 406, Springer-Verlag,. 14-AUG-11, . : ,
08/29/2011 53.00	I-Hong Hou, P. R. Kumar. A Survey of Recent Results on Real-Time Wireless Networking, Proceedings of Real-time Wireless for Industrial Applications. 11-APR-11, . : ,
09/06/2012 05.00	Krishna Jagannathan, Libin Jiang, Eytan Modiano. On Scheduling Algorithms Robust to Heavy-Tailed Traffic, Information Theory and Applications (ITA). 05-FEB-12, . : ,

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
04/10/2012	82.00	Jian Tan, Wei Wei, Bo Jiang, Ness Shroff, Don Towsley. Can Multipath Mitigate Power Law Delays? - Effects of Parallelism on Tail Performance, 2010 22nd International Teletraffic Congress (ITC 22). 07-SEP-10, . : ,
05/07/2012	22.00	Krishna Jagannathan, Mihalis Markakis, Eytan Modiano, John N. Tsitsiklis. Queue length asymptotics for generalized max-weight scheduling in the presence of heavy-tailed traffic, IEEE INFOCOM 2011 - IEEE Conference on Computer Communications. 10-APR-11, Shanghai, China. : ,
05/07/2012	79.00	Pedram Hovareshti, Hua Chen, John S. Baras. Motif-based Communication Network Formation for Task Specific Collaboration in Complex Environments, Proceedings 2011 American Control Conference. 29-JUN-11, . : ,
05/07/2012	37.00	P. R. Kumar, I-Hong Hou. Broadcasting Delay-Constrained Traffic over Unreliable Wireless Links with Network Coding, ACM MobiHoc . 16-MAY-11, . : ,
05/07/2012	35.00	Long B. Le, Eytan Modiano, Changhee Joo, Ness B. Shroff,. Longest-Queue-First Scheduling under SINR Interference Model, ACM MobiHoc. 20-SEP-10, . : ,
05/07/2012	34.00	Krishna Jaganathan, Ishai Menache, Eytan Modiano, Gil Zussman. Non-cooperative Spectrum Access - The Dedicated vs. Free Spectrum Choice, ACM MOBIHOC. 16-MAY-11, . : ,
05/07/2012	26.00	Krishna Jagannathan, Mihalis Markakis, Eytan Modiano, John N. Tsitsiklis. Throughput optimal scheduling in the presence of heavy-tailed traffic, 2010 48th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 29-SEP-10, Monticello, IL, USA. : ,
05/07/2012	25.00	Eytan Modiano, Guner D. Celik. Dynamic vehicle routing for data gathering in wireless networks, 2010 49th IEEE Conference on Decision and Control (CDC). 15-DEC-10, Atlanta, GA, USA. : ,
05/07/2012	24.00	Shie Mannor, Ishai Menache, Krishna Jagannathan, Eytan Modiano. A state action frequency approach to throughput maximization over uncertain wireless channels, IEEE INFOCOM 2011 - IEEE Conference on Computer Communications. 10-APR-11, Shanghai, China. : ,
05/07/2012	23.00	Guner D. Celik, Long B. Le, Eytan Modiano. Scheduling in parallel queues with randomly varying connectivity and switchover delay, IEEE INFOCOM 2011 - IEEE Conference on Computer Communications. 10-APR-11, Shanghai, China. : ,
08/18/2013	84.00	Nathaniel M. Jones, Brooke Shrader, Eytan Modiano. Distributed CSMA with pairwise coding, IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,
08/18/2013	86.00	Hulya Seferoglu, Eytan Modiano. Diff-Max: Separation of routing and scheduling in backpressure-based wireless networks, IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/18/2013 85.00 Chih-ping Li, Eytan Modiano. Receiver-based flow control for networks in overload,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/25/2012 86.00 Anh Truong, Santanu Chakraborty, P. R. Kumar, I-Hong Hou. Optimality of periodwise static priority policies in real-time communications,
2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011). 12-DEC-11, Orlando, FL, USA. : ,

08/25/2012 95.00 Guner D. Celik, Eytan Modiano. Scheduling in networks with time-varying channels and reconfiguration delay,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/25/2012 87.00 I-Hong Hou, P. R. Kumar. Scheduling Periodic Real-Time Tasks with Heterogeneous Reward Requirements,
2011 IEEE 32nd Real-Time Systems Symposium (RTSS). 29-NOV-11, Vienna, Austria. : ,

08/26/2012 90.00 Nikolaos Pappas, Jeongho Jeon, Anthony Ephremides, Apostolos Traganitis. Optimal utilization of a cognitive shared channel with a rechargeable primary source node,
2011 IEEE Information Theory Workshop (ITW). 16-OCT-11, Paraty, Brazil. : ,

08/26/2012 27.00 Nikolaos Pappas, Jeongho Jeon, Anthony Ephremides, Apostolos Traganitis. Wireless Network-Level Partial Relay Cooperation,
2012 IEEE International Symposium on Information Theory Proceedings. 01-JUL-12, . : ,

08/26/2012 25.00 Jeongho Jeon , Anthony Ephremides. Effect of Channel Estimation Errors on the Stability of Channel-Aware Random Access,
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08/26/2012 24.00 Pu Wang, Ian F. Akyildiz. Network stability of cognitive radio networks in the presence of heavy tailed traffic,
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08/26/2012 14.00 Timothy La Fond, Joseph J. Pfeiffer III, Sebastian Moreno, Jennifer Neville. Fast Generation of Large Scale Social Networks While Incorporating Transitive Closures,
Proceedings of the 4th ASE/IEEE InternationalConference on Social Computing, 2012. 03-SEP-12, . : ,

08/26/2012 13.00 Joseph J. Pfeiffer III, Jennifer Neville, Paul N. Bennett. Active Sampling of Networks,
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08/26/2012 12.00 Karthik Nagaraj, Charles Killian, Jennifer Neville. Structured Comparative Analysis of Systems Logs to Diagnose Performance Problems,
Proceedings of the 9th USENIX Symposium on Networked Systems Designand Implementation, 2012. 25-APR-12, . : ,

08/26/2012 20.00 G. Celik, S. Borst, P. Whiting, E. Modiano. Variable frame based Max-Weight algorithms for networks with switchover delay,
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08/26/2012 19.00 Nesreen K. Ahmed, Jennifer Neville, Ramana Kompella. Space-Efficient Sampling from Social Activity Streams,
Proceedings of the 1stInternational Workshop on Big Data, Streams and HeterogeneousSource Mining, KDD, 2012. 12-AUG-12, . : ,

08/26/2012 98.00 Murat Kantarcioglu, Yan Zhou, Bhavani Thuraisingham, Bowei Xi. Adversarial support vector machine learning,
the 18th ACM SIGKDD international conference. 12-AUG-12, Beijing, China. : ,

08/26/2012 97.00 Brooke Shrader, Eytan Modiano, Nathaniel M. Jones. Optimal routing and scheduling for a simple network coding scheme,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/26/2012 96.00 Mihalis G. Markakis, Eytan H. Modiano, John N. Tsitsiklis. Max-weight scheduling in networks with heavy-tailed traffic,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/28/2012 30.00 Shiyao Chen, Lang Tong, Qing Zhao. Delay optimal multichannel opportunistic access,
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08/28/2012 38.00 Yang Yang, Ness B. Shroff. Throughput of Rateless Codes over Broadcast ErasureChannels,
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08/28/2013 90.00 Mihalis Markakis, Eytan Modiano, John N. TSitsiklis. 7. Delay Analysis of the Max-Weight Policy under Heavy-Tailed Traffic via Fluid Approximations,
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08/29/2011 3.00 Sayan Mitra, P. R. Kumar, Kyoung-Dae Kim. Bounded ?-reachability of linear hybrid automata with a deterministic and transversal discrete transition condition,
2010 49th IEEE Conference on Decision and Control (CDC). 15-DEC-10, Atlanta, GA, USA. : ,

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Proc. of the IEEE Int'l Symposium on Information Theory. 31-JUL-11, . : ,

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08/29/2011 40.00 P. Kidwell, S. Guha, A. Barthur, W. S. Cleveland, J. Gerth, C. Bullard,. A Streaming Statistical Algorithm for Detection of SSH Keystroke Packets in TCP Connections,
Proceedings of 12th INFORMS Computing Society Conference. 09-JAN-11, . : ,

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Hybrid Systems: Computation and Control . 12-APR-11, . : ,

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2010 48th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 29-SEP-10, Monticello, IL, USA. : ,

08/29/2011 28.00 Ian F. Akyildiz, Pu Wang. Can dynamic spectrum access induce heavy tailed delay?,
2011 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN). 03-MAY-11, Aachen, Germany. : ,

08/29/2011 18.00 Shiyao Chen, Lang Tong. Distributed multiaccess in hierarchical cognitive radio networks,
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08/29/2011 17.00 Stefano Marano, Vincenzo Matta, Lang Tong. Embedding covert information flow,
2010 44th Asilomar Conference on Signals, Systems and Computers. 07-NOV-10, Pacific Grove, CA, USA. : ,

08/29/2011 16.00 Prithwish Basu, Abhishek Nadamani, Lang Tong. Extremum tracking in sensor fields with spatio-temporal correlation,
MILCOM 2010 - 2010 IEEE Military Communications Conference. 31-OCT-10, San Jose, CA, USA. : ,

08/29/2011 15.00 Jinsub Kim, Lang Tong. Detection of time-varying flows in wireless networks,
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08/29/2011 9.00 Jeongho Jeon, Anthony Ephremides. Neighbor discovery in a wireless sensor network: multipacket reception capability and physical-layer signal processing,
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08/29/2011 6.00 Zheng Zeng, Yan Gao, P.R. Kumar. SOFA: A Sleep-Optimal Fair-Attention Scheduler for the Power-Saving Mode of WLANs,
2011 31st International Conference on Distributed Computing Systems (ICDCS). 20-JUN-11, Minneapolis, MN, USA. : ,

08/29/2011 5.00 Zheng Zeng, Yan Gao, Kun Tan, P. R. Kumar. CHAIN: Introducing minimum controlled coordination into random access MAC,
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08/29/2011 4.00 Yan Gao, Chee Wei Tan, Ying Huang, Zheng Zeng, P. R. Kumar. Feasibility and optimization of delay guarantees for non-homogeneous flows in IEEE 802.11 WLANs,
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08/29/2012 39.00 Zizhan Zheng, Ness B. Shroff. Maximizing a Submodular Utility for DeadlineConstrained Data Collection in Sensor Networks,
IEEE 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOPT'12). 14-MAY-12, . : ,

08/29/2012 44.00 Wenzhuo Ouyang, Atilla Eryilmaz, Ness B. Shroff. Asymptotically optimal downlink scheduling over Markovian fading channels,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/29/2012 43.00 Srikanth Hariharan, Ness B. Shroff. On sample-path optimal dynamic scheduling for sum-queue minimization in trees under the K-hop interference model,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/29/2012 42.00 Jaemin Han, Chih-Chun Wang, Ness B. Shroff. Analysis of precoding-based intersession network coding and the corresponding 3-unicast interference alignment scheme,
2011 49th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 28-SEP-11, Monticello, IL, USA. : ,

08/29/2012 41.00 Shengbo Chen, Prasun Sinha, Ness B. Shroff, Changhee Joo. A simple asymptotically optimal energy allocation and routing scheme in rechargeable sensor networks,
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08/29/2012 40.00 Wenzhuo Ouyang, Atilla Eryilmaz, Ness B. Shroff. Low-complexity Optimal Scheduling overCorrelated Fading Channels with ARQ Feedback,
IEEE 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOPT'12). 14-MAY-12, . : ,

08/29/2013 16.00 Han Cai, Irem Koprulu, Ness B. Shroff. Exploiting double opportunities for deadline based content propagation in wireless networks,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 17.00 Zhoujia Mao, C. Emre Koksal, Ness B. Shroff. Online packet scheduling with hard deadlines in multihop communication networks,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 18.00 Yoora Kim, Kyunghan Lee, Ness B. Shroff, Injong Rhee. Providing probabilistic guarantees on the time of information spread in opportunistic networks,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 19.00 Bo Ji, Changhee Joo, Ness B. Shroff. Exploring the inefficiency and instability of Back-Pressure algorithms,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 20.00 Jia Liu, Cathy H. Xia, Ness B. Shroff, Hanif D. Sherali. Distributed cross-layer optimization in wireless networks: A second-order approach,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 21.00 Gagan R. Gupta, Xiaojun Lin, Bo Ji, Ness B. Shroff. Performance of low-complexity greedy scheduling policies in multi-channel wireless networks: Optimal throughput and near-optimal delay,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 22.00 Shuang Li, Zizhan Zheng, Eylem Ekici, Ness B. Shroff. Maximizing social welfare in operator-based Cognitive Radio Networks under spectrum uncertainty and sensing inaccuracy,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/29/2013 24.00 Zizhan Zheng, Eylem Ekici, Ness Shroff, Shuang Li. Maximizing system throughput using cooperative sensing in multi-channel cognitive radio networks,
2012 IEEE 51st Annual Conference on Decision and Control (CDC). 10-DEC-12, Maui, HI, USA. : ,

08/30/2012 49.00 Anthony Fanous, Anthony Ephremides. Effect of Secondary Nodes on the Primary's Stable Throughput in a Cognitive Wireless Network,
IEEE International Symposium on Information Theory. 01-JUL-12, . : ,

08/30/2012 52.00 Mohamed Kashef, Anthony Ephremides. Optimal Scheduling for Two Sources over TimeVarying Wireless Channels,
International Symposium on Information theory and Applications, Honolulu. 28-OCT-12, . : ,

08/30/2013 29.00 S. Moreno, J. Neville, S. Kirshner. Learning Mixed Kronecker Product Graph Models with Simulated Method of Moments,
Proceedings of the 19th ACM SIGKDD Conference on Knowledge Discovery and Data Mining. 10-AUG-13, . : ,

08/30/2013 30.00 R. Rossi, B. Gallagher, J. Neville, K. Henderson. Modeling Dynamic Behavior in Large Evolving Graphs,
Proceedings of the 6th ACM International Conference on Web Search and Data Mining. 04-FEB-13, . : ,

08/30/2013 31.00 N. Ahmed, J. Neville, R. Kompella.. Space-Efficient Sampling from Social Activity Streams,
Proceedings of the 1st International Workshop on Big Data, Streams and Heterogeneous Source Mining, KDD. 12-AUG-12, . : ,

08/30/2013 35.00 Eleni Stai, John S. Baras, Symeon Papavassiliou. A class of backpressure algorithms for networks embedded in hyperbolic space with controllable delay-throughput trade-off,
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08/30/2013 36.00 Ion Matei, Christoforos Somarakis, John S. Baras. A randomized gossip consensus algorithm on convex metric spaces,
2012 IEEE 51st Annual Conference on Decision and Control (CDC). 10-DEC-12, Maui, HI, USA. : ,

08/30/2013 37.00 K. Jain, J.S. Baras. Impact of Protocols on Traffic Burstiness at Large Timescales in Wireless Multi-Hop Networks,
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08/30/2013 39.00 D-H Sung, J.S. Baras, C. Zhu. Coordinated Scheduling and Power Control for Downlink Cross-tier Interference Mitigation in Heterogeneous Cellular Networks,
Proceedings 2013 IEEE Globecom. 09-DEC-13, . : ,

08/31/2012 59.00 John S. Baras, Vahid Tabatabaee, Kaustubh Jain. A model based platform for design and optimization of multi-hop 802.11 wireless networks,
the 8th ACM Symposium. 03-NOV-11, Miami, Florida, USA. : ,

08/31/2012 66.00 E. STAI, J. S. BARAS, S. PAPAVASSILIOU. THROUGHPUT-DELAY TRADE-OFF IN WIRELESS MULTIHOP NETWORKS VIA GREEDY HYPERBOLIC EMBEDDING,
Proceedings 20th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2012). 13-JUL-12, . : ,

08/31/2012 65.00 CHRISTOFOROS SOMARAKIS, JOHN S. BARAS. THE CONSENSUS PROBLEM UNDER VANISHINGCOMMUNICATIONS,
Proceedings of the 20th International Symposium on Mathematical Theory of Networks and Systems (MTNS 2012). 13-JUL-12, . : ,

08/31/2012 62.00 Senni Perumal, John S. Baras. Performance evaluation of single channel virtual-circuit MAC protocols for MANETs,
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08/31/2012 60.00 Shanshan Zheng, John S. Baras. Multi-scale analysis of long range dependent traffic for anomaly detection in wireless sensor networks,
2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011). 12-DEC-11, Orlando, FL, USA. : ,

09/01/2011 63.00 Sugumar Murugesan, Philip Schniter, Ness B. Shroff. Throughput/energy aware opportunistic transmission control in broadcast networks,
2010 48th Annual Allerton Conference on Communication, Control, and Computing (Allerton). 29-SEP-10, Monticello, IL, USA. : ,

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ACM MobiHoc. 16-MAY-11, . : ,

09/01/2011 72.00 Bo Ji, Changhee Joo, Ness B. Shroff. Scheduling with per-link queues and no per-flow information in multi-hop wireless networks,
2011 International Symposium of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Networks (WiOpt). 09-MAY-11, Princeton, NJ, USA. : ,

09/01/2011 71.00 Srikanth Hariharan, Ness B. Shroff. Deadline constrained scheduling for data aggregation in unreliable sensor networks,
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09/01/2011 70.00 Srikanth Hariharan, Ness B. Shroff. On optimal dynamic scheduling for sum-queue minimization in trees,
2011 International Symposium of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Networks (WiOpt). 09-MAY-11, Princeton, NJ, USA. : ,

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09/01/2011 68.00 Wenzhuo Ouyang, Sugumar Murugesan, Atilla Eryilmaz, Ness B. Shroff. Exploiting channel memory for joint estimation and scheduling in downlink networks,
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09/01/2011 67.00 Shengbo Chen, Prasun Sinha, Ness B. Shroff, Changhee Joo. Finite-horizon energy allocation and routing scheme in rechargeable sensor networks,
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09/01/2011 65.00 Sugumar Murugesan, Philip Schniter, Ness B. Shroff. Opportunistic scheduling using ARQ feedback in multi-cell downlink,
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09/03/2011 52.00 R. Xiang, J. Neville. Relational Learning with One Network: An Asymptotic Analysis, Proceedings of the 14th International Conference on Artificial Intelligence and Statistics. 11-APR-11, . : ,

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10/13/2014 50.00 Eytan Modiano, Matthew Johnston, Isaac Keslassy. Channel Probing in Communication Systems: Myopic Policies Are Not Always Optimal, IEEE International Symposium on Information Theory. 07-JUL-13, . : ,

10/13/2014 51.00 Mihalis G. Markakis, Eytan Modiano, John N. Tsitsiklis. Delay Analysis of the Max-Weight Policy under Heavy-Tailed Traffic via Fluid Approximations, Fifty-first Annual Allerton Conference. 02-OCT-13, . : ,

10/13/2014 52.00 Eytan Modiano, Matthew Johnston. Optimal Channel Probing in Communication Systems: The Two-Channel Case, IEEE Globecom. 09-DEC-13, . : ,

10/13/2014 53.00 Georgios S. Paschos, Chih-ping Li, Eytan Modiano, Kostas Choumas, Thanasis Korakis. Multirate Multicast: Optimal Algorithms and Implementation, IEEE Infocom. 27-APR-14, . : ,

10/13/2014 54.00 Kyu Seob Kim, Chih-ping Li, Eytan Modiano. Scheduling Multicast Traffic with Deadlines in Wireless Networks, IEEE Infocom. 27-APR-14, . : ,

10/13/2014 55.00 Mihalis G. Markakis, Eytan Modiano, John N. Tsitsiklis. Delay Stability of Back-Pressure Policies in the presence of Heavy-Tailed Traffic, Information Theory and Applications. 09-FEB-14, . : ,

10/13/2014 56.00 Chih-ping Li, Georgios S. Paschos, Leandros Tassiulas, Eytan Modiano. Dynamic Overload Balancing in Server Farms, Networking. 02-JUN-14, . : ,

10/13/2014 57.00 Matthew Johnston, Eytan Modiano, Yury Polyanskiy. Opportunistic Scheduling with Limited Channel State Information: A Rate Distortion Approach, IEEE International Symposium on Information Theory. 29-JUN-14, . : ,

10/14/2014 70.00 Rahul Singh, I-Hong Hou, P. R. Kumar. Fluctuation Analysis of Debt Based Policies for Wireless Networks with Hard Delay Constraints, Infocom 2014. 27-APR-14, . : ,

TOTAL: 108

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
08/18/2013 77.00	Kyoung-Dae Kim, P. R. Kumar,. An Overview and Some Challenges of Cyber-PhysicalSystems, (05 2013)
08/18/2013 78.00	Kyoung-Dae Kim, P. R. Kumar. Intersection Crossing: An MPC-based Approach for Provable System-wide Safety and Liveness of Autonomous Ground Traffic., IEEE Transactions on Automatic Control (02 2013)
08/25/2012 99.00	Kyoung-Dae Kim, P. R. Kumar. A Real-Time Middleware for Networked ControlSystems and Application to an Unstable System, IEEE Transactions on Control Systems Technology (06 2011)
08/25/2012 06.00	Krishna Jagannathan, Shie Mannor, Ishai Menache, Eytan Modiano. A State Action Frequency Approach to Throughput Maximization over Uncertain Wireless Channels, INTERNET MATH (12 2012)
08/25/2012 04.00	Anand Muralidhar, P. R. Kumar. Near-optimal quantization and linear network coding for relay networks, IEEE TRANSACTIONS ON INFORMATION THEORY (03 2012)
08/25/2012 03.00	Jonathan Ponniah, Yih-Chun Hu, P.R Kumar. Secure Network Discovery in the Presence of Malicious Nodes, OPODIS 2012: 16th International Conference On Principles Of Distributed Systems (07 2012)
08/25/2012 01.00	Hemant Kowshik, P. R. Kumar. Optimal Computation of Symmetric Boolean Functions in Collocated Networks, IEEE Journal on Selected Areas in Communications: In-Network Computation: Exploring the Fundamental Limits (02 2012)
08/25/2012 00.00	Kyoung-Dae Kim, Sayan Mitra, P. R. Kumar. Bounded ?-Reach Set Computation of a Class of Deterministic and Transversal Linear Hybrid Automata, IEEE Transactions on Automatic Control (05 2012)
08/26/2012 07.00	Krishna Jagannathan, Ishai Menache, Eytan Modiano, Gil Zussman. Non-cooperative Spectrum Access – The Dedicated vs. Free Spectrum Choice, IEEE JSAC: Special Issue on Economics of Communication Networks & Systems (12 2011)
08/26/2012 26.00	Pu Wang, Ian F. Akyildiz. Mobility Improves Latency in Cognitive Radio Networks with Heavy Tailed Spectrum Activities, IEEE Infocom 2013 (07 2012)
08/26/2012 21.00	Ian F. Akyildiz, Pu Wang. Asymptotic Queueing Analysis for DynamicSpectrum Access Networks in the Presence ofHeavy tails, IEEE Journal on Selected Areas in Communications (08 2012)
08/26/2012 16.00	DAVID ANDERSON, WILLIAM S. CLEVELAND, BOWEI XI. MULTIFRACTAL AND GAUSSIAN FRACTIONAL SUM-DIFFERENCE MODELS FOR INTERNET TRAFFIC: VALIDATION, Annals ofApplied Statistics (09 2011)
08/28/2012 29.00	Yan Gao, Chee Wei Tan, Ying Huang, Member, Zheng Zeng, P. R. Kumar. Characterization and Optimization of Mean DelayGuarantees for Non-homogeneous Flows in IEEE802.11 WLANs, IEEE Transactions on Networking. (09 2011)

08/28/2013 91.00 Pu Wang, Ian F. Akyildiz. Improving Network Connectivity in the Presence of Heavy-Tailed Interference,
IEEE Transactions on Wireless Communications (07 2013)

08/28/2013 92.00 Pu Wang, Ian F. Akyildiz. On the Stability of Dynamic Spectrum Access Networks in the Presence of Heavy Tails,
IEEE Transactions on Wireless Communications (07 2013)

08/29/2011 36.00 D.A. Anderson, W. S. Cleveland, Bowei Xi. Multifractal and GaussianFractional Sum-Difference Models for Internet Traffic.,
Annals of Applied Statistics (08 2011)

08/30/2012 50.00 Mohamed Kashef , Anthony Ephremides. Stability Analysis for Energy Harvesting Sources over Time Varying Wireless Channels with Relays,
IEEE Infocom 2013 (07 2012)

08/30/2012 51.00 Maice Costa, Anthony Ephremides. Trade-off of Energy Efficiency versus Performancein Cognitive Wireless Networks,
IEEE Infocom 2013 (07 2012)

08/30/2013 41.00 Eleni Stai, Symeon Papavassiliou, John S. Baras. Performance-Aware Cross-layer Design in Wireless Multihop Networks via a Weighted Backpressure Approach,
IEEE/ACM Transactions on Networking (07 2013)

08/31/2012 53.00 Shuang Li, Eylem Ekici, Ness Shroff. Throughput Optimal Queue Length BasedCSMA/CA Algorithm for Cognitive RadioNetworks,
IEEE TRANSACTIONS ON Wireless Communications (06 2012)

08/31/2012 73.00 Jeongho Jeon, Anthony Ephremides. On the Stability of Random Multiple Access with Stochastic Energy Harvesting,
IEEE TRANSACTIONS ON INFORMATION THEORY (05 2012)

08/31/2012 64.00 CHRISTOFOROS SOMARAKIS, JOHN S. BARAS. ON THE DYNAMICS OF A SIMPLERATIONAL PLANAR MAP,
International Journal of Bifurcation and Chaos (05 2012)

08/31/2012 63.00 Christoforos Somarakis, Ion Matei, John S. Baras. A randomized gossip consensus algorithm on convex metric spaces,
Proceedings 2012 IEEE Conference on Decision and Control, CDC2012. (03 2012)

08/31/2012 58.00 B. T. Swapna, Atilla Eryilmaz, Ness B. Shroff. Throughput-Delay Analysis of Random LinearNetwork Coding for Wireless Broadcasting,
IEEE TRANSACTIONS ON INFORMATION THEORY (06 2012)

08/31/2012 57.00 Jian Tan, B. T. Swapna, Ness B. Shroff. Retransmission Delays with Bounded Packets : Power law body and Exponential tail,
IEEE Transactions on Networking. (05 2012)

08/31/2012 56.00 Yang Yang, Jian Tan, Ness B. Shroff, Hesham El Gamal. Delay Asymptotics with Retransmissions andIncremental Redundancy Codes over ErasureChannels,
IEEE TRANSACTIONS ON INFORMATION THEORY (02 2012)

08/31/2012 55.00 Yang Yang, Ness B. Shroff. Throughput of Rateless Codes over Broadcast Erasure Channels,
IEEE Transactions on Networking (07 2012)

08/31/2012 54.00 Wenzhuo Ouyang, Sugumar Murugesan, Atilla Eryilmaz, Ness B. Shroff. Exploiting Channel Memory for Joint Estimation and Scheduling in Downlink Networks– A Whittle’s Indexability Analysis,
IEEE TRANSACTIONS ON INFORMATION THEORY (09 2011)

09/06/2012 02.00 Jonathan Ponniah, Yih-Chun Hu, P.R Kumar. Secure Clock Synchronization in the Presence of Malicious Agents,
OPODIS 2012: 16th International Conference On Principles Of Distributed Systems (07 2012)

09/06/2012 15.00 WILLIAM S. CLEVELAND, BOWEI XI, DAVID ANDERSON. MULTIFRACTAL AND GAUSSIAN FRACTIONAL SUM-DIFFERENCE MODELS FOR INTERNET TRAFFIC,
Annals of Applied Statistics (09 2011)

10/10/2014 47.00 Eytan Modiano, Güner D. Çelik. Scheduling in Networks with Time-Varying Channels and Reconfiguration Delay,
IEEE/ACM Trans. on Networking (2014)

10/13/2014 43.00 Ian F. Akyildiz, Pu Wang. On the Stability of Dynamic Spectrum Access Networks in the Presence of Heavy Tails,
IEEE Transactions on Wireless Communications (10 2014)

10/13/2014 44.00 Pu Wang, Ian F. Akyildiz. Improving Network Connectivity in the Presence of Heavy-Tailed Interference,
IEEE Transactions on Wireless Communications (10 2014)

10/13/2014 45.00 Chih-ping Li, Eytan Modiano. Receiver-Based Flow Control for Networks in Overload,
IEEE/ACM Trans. on Networking (10 2014)

TOTAL: **34**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

09/05/2013 94.00 Zhoujia Mao, C. Emre Koksal, Ness B. Shroff. Cross-Layer Resource Allocation in Energy Harvesting Sensor Networks, World Scientific: World Scientific Publishing, (03 2013)

TOTAL: **1**

Patents Submitted

Patents Awarded

Awards

Eytan Modiano is selected to serve on IEEE Fellows committee.

Ian Akyildiz received Humboldt Research Award from German Humboldt Foundation in November 2013. Dr. Akyildiz will be conducting research on TeraHertzBand with University of Erlangen-Nurnberg, Department of Digital Communication, within the next three years.

Ness Shroff received the IEEE INFOCOM achievement award for "seminal contributions to scheduling and resource allocation in wireless networks".

Ness Shroff is cited on list of Most highly cited researchers Thomson Reuters ISI.

Ness Shroff appears on the list of The World's Most Influential Scientific Minds in 2014.

Ness Shroff has accepted a visiting professorship at the IIT Bombay, 2014.

Ness Shroff has been invited to the distinguished colloquium presentation at the University of Maryland’s Mpact Week on Disaster Resilience.

P. R. Kumar, University Distinguished Professor, Texas A&M University, April 30, 2014 -- .

P. R. Kumar, Holder of College of Engineering Chair in Computer Engineering, 2011 -- .

P. R. Kumar, ACM Fellow, 2013.
``For contributions to wireless communication and control technologies."

P. R. Kumar, D.J. Gandhi Distinguished Visiting Professor,
Department of Electrical Engineering, IIT Bombay, 2013 --.

P. R. Kumar, Visiting Professor, Robert Bosch Centre for Cyber Physical Systems,
Indian Institute of Science, Bangalore, August 2013--August 2015.

Keynote speeches

Ian Akyildiz, Distinguished Seminar on "Nanoscale Communication Networks" at Al Faisal University, Riyadh, Saudi Arabia, on Nov. 20, 2013.

Ian Akyildiz, Tutorial on "Wireless Sensor Networks" at KACST (King Abdullah Council for Science and Technology) (Saudi Arabia NSF) on Nov 20, 2013.

Ian Akyildiz, Keynote speech on "Underground and Underwater Wireless Sensor Networks" at KACST (King Abdullah Council for Science and Technology) (Saudi Arabia NSF) on Nov 19, 2013.

Ian Akyildiz, Invited speech on "Smart Grid: Research Challenges" at King Abdulaziz University in Jeddah, Saudi Arabia on Nov 18, 2013.

Ian Akyildiz, Invited speech on "LTE-A: Research Challenges" at King Abdulaziz University in Jeddah, Saudi Arabia on Nov. 17, 2013.

Ian Akyildiz, Keynote speech on "Nanonetworks: A New Communication Paradigm" at Turgut Ozal University, Nov 13, 2013.

Ian Akyildiz, Distinguished Seminar entitled "Graphene-based Nano-scale Communication Networks in Terahertz Band" at the Norwegian University of Technology and Science (NTNU), Trondheim, Norway, Oct. 17, 2013.

Ian Akyildiz, Keynote speech entitled "Rocking the World Nanoscale: Future Internet Research for Communication Networks in Medicine, Health and Beyond" at the VERDIKT-Conference "Rock 'n' Roll Technologies" organized by the Research Council of Norway, Trondheim, Norway, Oct. 15, 2013.

Ian Akyildiz, Interview by the Research Council of Norway - VERDIKT, regarding his pioneering research on on molecular communication for nanomedicine, on October 2013

Ian Akyildiz, Interview by the Communications of the ACM, regarding his pioneering research on graphane-based nano-antennas for wireless communication in the terahertz band, on October 2013.

Ian Akyildiz, Invited seminar entitled "Nanonetworks: A New Frontier in Communications" at the National Research University of Information Technologies, Mechanics and Optics (NRU ITMO), St. Petersburg, Russia, Sept. 24, 2013.

Ian Akyildiz, Invited seminar entitled "Nanonetworks: A New Frontier in Communications" at the University of Iceland, Reykjavik, September 12, 2013.

P.R. Kumar, Plenary Speaker, Twentieth National Conference on Communications (NCC), Kanpur, India, Feb 28, 2014.

P. R. Kumar, Distinguished Visitor Talk, Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada, Jan 27, 2014.

P. R. Kumar, Plenary Speaker, 2013 Annual IEEE India Conference (INDICON), Bombay, Dec 15, 2013.

P.R. Kumar Keynote Speaker, Cyber-Physical Systems Week (CPSWeek) 2014}. Berlin, Germany, April 15-17, 2014. https://www.cpsweek2014.org/cpsweek2014/index.html

P.R. Kumar, Keynote Speaker,IEEE International Conference on Computer Communications (INFOCOM 2014). Toronto, Canada, April 27--May 2, 2014. http://www.indicon2013.org

P. R. Kumar, Keynote Speaker, The Fourth International Workshop on Cross-Layer Design (IWCLD 2013), Qingdao, China, Oct 28--29, 2013.

P. R. Kumar, Keynote Speaker, 2013 International Conference on Wireless Communications and Signal Processing (WCSP 2013). Hangzhou, China, Oct 24--26, 2013.

P.R. Kumar, Computer Science Distinguished Speakers Series, College of William and Mary, Williamsburg, VA, October 18, 2013.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Abhishek Sinha	1.00	
Zhoujia Mao	0.25	
Ke Ma	0.75	
Xi Liu	0.08	
FTE Equivalent:	**2.08**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Chih-Ping Li	0.33
Zizhan Zheng	0.16
Yoora Kim	0.16
Jonathan Ponniah	0.17
Abhishek Halder	0.17
FTE Equivalent:	**0.99**
Total Number:	**5**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Eytan Modiano	0.05	
Ness Shroff	0.06	
P. R. Kumar	0.08	Yes
Lang Tong	0.00	
Ian Akyildiz	0.00	
FTE Equivalent:	**0.19**	
Total Number:	**5**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ......

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Pu Wang	
Zhoujia Mao	
Wenzhuo Ouyang	
Mihalis Markakis	
Total Number:	**4**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Contributions:
Some of our major contributions during the project duration are outlined below:

1. Developed a unifying framework for designing low-complexity scheduling policies in the downlink of multi-channel wireless networks that can provide optimal performance in terms of both throughput and delay.
2. Studied optimal control of wireless transmissions over multi-scale time-varying channels.
3. Explored whether heavy-tails in traffic sources lead to long-range dependence in aggregate traffic and studied the impact of protocol dynamics. We found that, unlike in TCP scenarios, the UDP traffic is not LRD. We concluded that the LRD nature of wireless network traffic due to heavy-tails in traffic sources cannot be taken for granted.
4. Investigated the impact of the protocol stack on traffic burstiness at large time-scales in wireless multi-hop network traffic.
5. Completed the development of a model-based platform for design and optimization of multi-hop 802.11 wireless networks.
6. Completed the investigation of frameworks for robust pruning in MANET routing and hierarchical routing. Our work has led to new solutions and algorithms for pruning and topology dissemination for MANET.
7. Developed a coordinated scheduling and power control algorithm for heterogeneous cellular networks.
8. Extended our earlier analysis of the impact of heavy-tailed traffic on the performance of scheduling in single hop networks to multi-hop networks, where routing of traffic can also lead to the delay propagation phenomenon.
9. Studied the impact of heavy tailed spectrum on the queueing delay and stability of dynamic spectrum access (DSA) networks.
10. Investigated the control of wireless systems under imperfect and even unknown channel information, which is likely to occur in military networks.
11. Analyzed the contact time distribution in mobile networking systems, which is critical for understanding the fundamental delay capacity tradeoffs in wireless networks.
12. Studied the impact of heavy-tailed spectrum activities on the network connectivity as well as how and to what extent mobility can mitigate such impact.
13. Investigated methods and metrics for real-time communication over unreliable wireless channels.
14. Developed a framework that outlines the complete spectrum of computational models for network sampling and explored methods of network sampling that generalize across a broad spectrum going from the easiest and least constrained model of static graphs to the more difficult and realistic model of sampling from graph streams.
15. Developed statistical models of networks that accurately capture the characteristics (e.g.. clustering) observed in real-world networks, while still providing natural variation in the generated graphs.
16. Obtained significant progress in analyzing DNS data.
17. Completed our investigation of the effects of LRD phenomena on the detection against important attacks on MANET Protocols
18. Obtained a characterization of embedding capacity provided by a pair of independent renewal processes.

A more detailed account of our accomplishments during the project duration is as following:

Area 1: Traffic Modeling and Performance Analysis for Multi-scale Networks

(1) Modeling LRD Traffic for Network Control
In most networks, the high variability in traffic sources, characterized by heavy-tail distributions, has been attributed as one of the main
causes of traffic LRD. In particular, heavy-tails in file size, connection or flow durations, inter-arrival times etc. have been empirically
verified in such networks. And, through the fundamental result on On/Off model by Taqqu et al., the causal link between heavy-tails and
LRD in an idealized setting has been established. Even though idealized, the result and its variations, have been applied with great success
in many real- measurements as well as simulation-based studies. The wide applicability of the model in various network settings has led to
the belief that the network protocols themselves play little part in large-time scale behavior of traffic rate, and that the protocol dynamics
affect only the small-time scale properties. While the existence of heavy-tails and LRD has been widely studied in wireline networks, there
are very few studies in wireless networks. Given the belief that network protocols won't affect large time scale behavior, it is generally
expected that wireless networks will yield similar result. However LRD phenomena in wireless networks can be qualitatively and quantitatively different from those detected in wired networks, as they include a number of new features such as mobility, fading as well as
the hidden/exposed node problem. While these features can cause increased variability in the service times, they may also result in

increased losses. Besides TCP and other congestion control mechanism behave differently in wireline and wireless networks due to fading.
The lower-layer protocols are expected to have more pronounced impact in wireless networks, and in some cases, themselves induce
heavy-tailed delays due to retransmissions.

We completed our investigation of the impact of wireless network protocols on traffic characteristics, in terms of traffic burstiness, self-similarity and long range dependence. In particular, we explored whether heavy-tails in traffic sources indeed lead to self similarity in aggregate traffic, especially in a wireless multi-hop setting. In the past, heavy-tails in file size, connection or flow durations, inter-arrival times etc. have been empirically verified in wire-line
networks with self-similar aggregate traffic. In our research, we strived to find conditions under which the relationship between heavy-tails and self-similarity holds, and similarly find conditions under which the traffic levels and network protocols destroy this relationship.

We completed our investigation of the impact of the protocol stack on long range dependence in wireless network traffic. In particular, we explored whether heavy-tails in traffic sources lead to long-range dependence (LRD) in aggregate traffic and studied the impact of protocol dynamics. In our analytical and simulation-based studies, we use traffic sources with heavy-tailed file sizes or interrequest times using UDP transport and 802.11 MAC, and performed statistical analysis to identify the degree of LRD. We found that, unlike in TCP scenarios, the UDP traffic is not LRD. While
wavelet analysis of UDP traffic shows scaling at small-time scales, the scaling is not preserved at largetime scales. We concluded that the LRD nature of wireless network traffic due to heavy-tails in traffic sources cannot be taken for granted.

We further investigated in more detail the impact of the protocol stack on traffic burstiness at large time-scales in wireless multi-hop network traffic. Origins of traffic burstiness at large scales (like its LRD nature) have been mostly attributed to the heavy-tails in traffic sources. In wired networks, protocol dynamics have little impact on large time-scale dynamics. However, given the nature of wireless networks, the MAC and routing layers together can lead to route flapping or oscillations even in a static network. Hence, we explored whether these dynamics can lead to traffic burstiness and LRD.

Using analysis and network simulations, we investigated the traffic characteristics for two MANET routing protocols - OLSR and AODV. By varying the routing protocol parameters, we analyzed their role in inducing or preventing route oscillations, and studied their impact on traffic LRD. We found that, losses in OLSR control packets, due to congestion at the MAC, can lead to route oscillations and traffic burstiness at large timescales. By tuning the parameters, route oscillations and traffic LRD can be avoided. AODV dynamics showed little evidence for traffic LRD, even though we cannot rule out this possibility. We also showed that the route oscillations can have heavier body and tail than exponential
distribution, and that the Markovian framework for route oscillations is inadequate to explain the observed traffic scaling. Lastly, we developed a model that captures the MAC and OLSR routing protocol interactions and depending upon the chosen protocol parameters and input load, correctly predicts the presence of traffic LRD. Thus, we used this model to design appropriate choice of protocol parameters to mitigate traffic burstiness at large-timescales.

We also completed the development of a model-based platform
for design and optimization of multi-hop 802.11 wireless networks. We developed a loss
model for multi-hop wireless networks based on IEEE 802.11 MAC. The model is defined as an
implicit function amongst the variables in the model and solved using a fixed point approach. Further, using Automatic Differentiation (AD) on the implicit function, we performed sensitivity analysis and used it in an optimization framework. As an illustration of how this model can help in design and optimization of wireless networks, we optimized the network throughput by appropriate load splitting along multiple paths. We validated our models using network simulations and data supplied to us by our collaborators at RDECOM/CERDEC.

2) Statistical Analysis and Modeling of Root Server DNS Traffic:
Verisign manages the domain name root servers for the .net and .com domains. DNS is a critical part of the control plane of the Internet, and so is a very inviting target for hackers. Many attacks have succeeded and a big one could do immense damage, so
DNS is given very priority by the U.S. Government both for
protection against attack and for good performance. Recently, a secure DNS was developed called DNSSEC, spearheaded by the U.S. Department of Homeland Security. We made significant progress in analyzing DNS data.
We collected Verisign root server data at Amsterdam
from Feb 2012 to July 2012 (2TB). Besides other analysis
results, we discovered botnet connections in DNS data. We are
currently pursuing more detailed statistical
analysis of the DNS botnet connections.

3) Akamai Traceroute Data Analysis:

We analyzed roughly 2 weeks of the Akamai traceroute data (300GB). Our statistical analysis focused on the traceroute round trip times (RTT). Some traceroutes may contain invalid path segments. Such traceroutes need to be identified and filtered out. We studied the data on a per-traceroute basis and on a per-link basis. We discovered a very strong linear relationship between traceroute RTT and total propagation RTT on the log scale. We are currently pursuing more detailed analysis of RTT.

4) Akamai CIDR Data Analysis:
We analyzed 78 weeks of data: (1) Total hourly values of aggregated individual CIDRs supplied in the raw data; (2) Total aggregated "other" CIDRs; these others were available as aggregates by subcategory. (3) Individual CIDRs aggregated by category; (4) Other CIDRs aggregated by category; (5) Individual CIDRs aggregated by geographical locality

The objectives of our analyses are: (1) accurate modeling of hourly hits for many different aggregations of CIDRs producing many hourly time serie each of length 7200; (2) forecasting of future hourly values; (3) anomaly detection.

The data have many anomalies which greatly complicates analysis. Some are readily explained. Others are not. Methods must be "robust" to them, that is, able to describe normal patterns withpout being distorted by them. Only by determining what is normal can we determine in an automated statistical way what the anomalies are. Our methods do a very good job of determining anomalies by iterative re-weighting methods.

5) Statistical Models of Network Structure

We have developed a mixed-KPGM (mKPGM) graph model, which is a generalization of the KPGM that uses parameter tying to model dependencies among edges. These dependencies enable the model to more accurately capture the clustering observed in real-world networks. The dependencies also increase the variance of the estimated distribution while preserving the expectation---thus mKPGMs are able to more accurately capture the natural variation observed in real-world network populations. However, the parameter tying makes it more difficult to learn the model parameters from observed data (due to edge dependencies). Recently, we have outlined the first tractable learning algorithm for mKPGMs. The algorithm is based on simulated method of moments where the distance between the observed moments in the training data and the empirically estimated moments of the model is minimized using constrained line search for continuous optimization. We have evaluated the proposed mKPGM learning algorithm by comparing to several alternative graph models, including KPGMs, on six real-world network domains. The results show that mKPGMs are able to capture the characteristics of the real-world graphs more accurately, while still providing natural variation in the generated graphs.

6) Impact of heavy-tailed traffic on network performance:
We first studied the fundamental impact of heavy tailed environment on the stability of dynamic spectrum access (DSA) networks. More specifically, we define a new stability criterion, namely moment stability, to characterize the QoS performance of DSA networks in the presence of heavy-tailed traffic. Then, we derive the stability region of DSA networks and reveal the underlying relationship between the stability region and the networks settings regarding primary networks and DSA networks. Next, we show that the classic maximum weight scheduling fails to achieve moment stability in the presence of heavy tailed traffic even though SUs can exploit the transmission opportunities of multiple wireless channels. Finally, we prove that under maximum-weight-alpha scheduling algorithm, DSA network can achieve the maximum throughput, while maintaining moment

stability, and we also demonstrate such throughput optimality is independent of the traffic statistics of network users, including the marginal distribution and time correlation structure of the traffic flows

We next study the fundamental impact of heavy tailed spectrum activities on the network connectivity as well as how and to what extent mobility can mitigate such impact. We consider a heterogeneous network setting, where there exist two networks: the primary network and the secondary network, where the primary networks either have the higher priority to access the spectrum than the secondary ones, as enforced by the emerging dynamic spectrum access scheme, or have much higher power to interfere the coexisting networks, such as the high power WiFi networks coexisting with the low-power wireless sensor networks. More specifically, we show that such heavy tailed traffic activities of primary network significantly degrade the connectivity of secondary network. In particular, we prove that if the busy time of primary users is heavy tail distributed, there always exists a critical density lambda_p such that if the density of primary users is larger than lambda lambda_p, the secondary network cannot achieve delay bounded connectivity surely, which simultaneously ensures the existence of routing paths and the finiteness of the delay variance along these paths To encounter this problem, the mobility of secondary users is utilized to exploit the spatial diversity of the spectrum availability through the opportunistic contacts of mobile users. In particular, we prove that there exists a critical threshold on the maximum radius the secondary user can reach, above which the secondary network can already achieve delay-bounded connectivity, independent of primary network impact such as node density and activities. Moreover, we study the latency performance of the mobility assisted data forward schemes, which shows that their yielded end-to-end latency scales linearly in the initial distance between two mobile users

Area 2 - Multi-scale Network Control

1) Low-Complexity Scheduling Policies with optimal throughput and delay performance:
The dramatic increases in demands from multimedia applications have put an enormous strain on the current cellular system infrastructure.
This has resulted in significant research and development efforts on 4G multi-channel wireless cellular systems (e.g., LTE and WiMax) that target new ways to achieve higher data rates, lower latencies, and a much better user experience. An important requirement for achieving these goals is to design efficient scheduling policies that can simultaneously provide high throughput and low delay. In these multi-channel systems, such as OFDM, the Transmission Time Interval (TTI), within which the scheduling decisions need to be made, is typically on the order of a few milliseconds. On the other hand, there are hundreds of orthogonal channels that can be allocated to different users. Hence, many decisions have to be made within a short scheduling cycle, which means that it is critical that scheduling policies must be of low complexity.
In recent groundbreaking work, we have developed a unifying framework for designing low-complexity scheduling policies in the downlink of multi-channel (e.g., OFDM-based) wireless networks that can provide optimal performance in terms of both throughput and delay. We first develop new easy-to verify sufficient conditions for rate-function delay-optimality in the many-channel many-user asymptotic regime, and for throughput-optimality in general (non-asymptotic) settings. The sufficient conditions enable us to prove rate-function delay-optimality for a class of Oldest Packets First (OPF) policies and throughput optimality for a large class of Maximum Weight in the Fluid limit (MWF) policies. By intelligently combining policies from the classes of OPF policies and MWF policies, we design hybrid policies that have a low complexity of O(n^{2.5} log n), which brings a complexity reduction from O(n^5), the best known existing algorithm, and is yet both throughput and rate-function optimal. We further develop two simpler greedy policies with complexity O(n^2) that are throughput-optimal and have provably near optimal delay. This work makes significant headway in the development of low-complexity algorithms for the emerging 4G multi-channel wireless systems.

2) Pruning and Topology dissemination for MANET:
We completed the investigation of partially ordered semiring frameworks for robust pruning in MANET routing and hierarchical routing as well as multi-metric problems in multiscale networks and analyzed connections to the Algebraic Stochastic Shortest Path Problem which led to new solutions and algorithms for pruning and topology dissemination for MANET. We introduced and investigated the stable path topology control problem for link-state routing in mobile multihop networks. We introduced a new topology control algorithm that guarantees stable path routing: a mechanism that prunes the initial topology (to reduce the broadcast storm) while guaranteeing that the stable paths (for unicast routing) from every host to any target station are preserved in the pruned topology. We developed a multiagent optimization framework where the decision policies of each agent are restricted to local policies on incident edges and independent of the policies of other agents. We showed that under a condition called the positivity condition, these independent local policies preserve the stable routing paths globally. We also provided an efficient and distributed algorithm, which we call the Stable Path Topology Control Algorithm, to compute this local policy that yields a pruned graph.
Using simulations, we demonstrated that this algorithm, when used with the popular ETX metric, outperforms topology control mechanisms commonly used for Mobile Ad Hoc Networks (MANET). A patent was awarded for this new algorithm.

3) A Class of Backpressure Algorithms for Networks Embedded in Hyperbolic Space with Controllable Delay-Throughput Trade-off
Future communications will consist of an increasing number of wireless parts, while simultaneously need to support the

widespread multimedia applications imposed by social networks. These human-machine systems, driven by both real time social interactions and the challenges of the wireless networks' design, call for efficient and easy to implement, distributed cross-layer algorithms for their operation. Performance metrics such as throughput, delay, trust, energy consumption, need to be improved and optimized aiming at high quality communications. The backpressure algorithm, has received much attention by the research community in the past few years, as it satisfies the throughput optimal requirement. The backpressure algorithm performs routing and scheduling based
n congestion gradients, by allowing transmission to the links that maximize the differential backlog between neighboring nodes. However, by deploying routing without using any information about the position or distance to the destination, it explores all possible source-destination paths leading to undesirable high delays. In our recent work, we investigated the throughput-delay trade-off in static wireless multihop networks based on a "computer-aided" design of the backpressure scheduling/routing algorithm for networks embedded in hyperbolic space. Both routing and scheduling exploit the hyperbolic distances to orient the packets to the destination and prioritize the transmissions correspondingly. The proposed design provides us with the freedom of controlling its theoretical throughput optimality and of counterbalancing its practical performance through simulations, leading to significant improvements of the throughput-delay trade-off.

4)Performance-Aware Cross-Layer Design in Wireless Multihop Networks via a Weighted Backpressure Approach
In the area of multi-metric optimization problems in multi-scale networks, we studied, analyzed and evaluated a performance-aware cross-layer design approach for wireless multihop networks. Through Network Utility Maximization (NUM) and weighted network graph modeling, a cross-layer algorithm for performing jointly routing, scheduling and congestion control was introduced. The performance-awareness is achieved by both the appropriate definition of the link weights for the corresponding application's requirements and the introduction of a weighted backpressure routing/scheduling. Contrary to the conventional backpressure the proposed
algorithm scales the congestion gradients with the appropriately defined link weights. We analytically proved the queue stability achieved by the proposed cross-layer scheme, while its convergence to a close neighborhood of the optimal source rates' values was proved via a novel e-subgradient approach.
Finally, through modeling and simulation, we demonstrated the performance improvements that can be achieved by the proposed approach - when compared against existing methodologies in the literature - for two different examples with diverse application requirements, emphasizing respectively on delay and trustworthiness.

4) Randomized Gossip algorithm for solving the generalized consensus problem:
A consensus problem consists of a group of dynamic agents who seek to agree upon certain quantities of interest using only local information in a distributed and asynchronous manner. It is a prototypical distributed optimization problem in networked systems with numerous applications. This problem can be generalized in the context of convex metric spaces that extend the standard notion of convexity. We completed the development and analysis of a randomized gossip algorithm for solving the generalized consensus problem on convex metric spaces. We studied the convergence properties of the algorithm using stochastic differential equations theory. We showed that the dynamics of the distances between the states of the agents can be upper bounded by the dynamics of a stochastic differential equation driven by Poisson counters. In addition, we introduced instances of the generalized consensus algorithm for several practical examples of convex metric spaces.

5) Packet scheduling with a mix of heavy-tailed and light-tailed traffic
We consider the problem of packet scheduling in a single-hop network with a mix of heavy-tailed and light-tailed traffic, and analyze the impact of heavy-tailed traffic on the performance of Max-Weight scheduling. This past year we extended our results to multi-hop networks, where routing of traffic can also lead to the delay propagation phenomenon. We study scheduling and routing problems that arise in multi-hop networks with a mix of heavy-tailed and light-tailed traffic. We analyze the delay performance of the widely studied class of Back-Pressure policies, known for their throughput optimality property, using as a performance criterion the notion of delay stability, i.e., whether the expected end-to-end delay in steady state is finite. We demonstrate that the network topology, the routing constraints, and the link capacities may affect the delay performance of the Back-Pressure policy in the presence of heavy-tailed traffic. We also develop a fluid approximation methodology that facilitates the delay-stability analysis of multi-hop networks with heavy-tailed traffic. This approach allows us to derive analytical results that would have been hard to obtain otherwise, and also to build a Bottleneck Identification algorithm, which identifies delay unstable queues by solving the fluid model of the network from certain initial conditions. Finally, we show how one can achieve optimal performance, with respect to the delay stability criterion, by using a parameterized version of the Back-Pressure policy.

6) Optimal Channel Probing for Time Varying Channels
In another line of work, we study optimal channel probing schemes for transmission over time-varying channels. We consider a multi-channel

communication system in which a transmitter has access to M channels, but does not know the state of any of the channels. We model the channel state using an ON/OFF Markov process, and allow the transmitter to probe a single channel at predetermined probing intervals to decide over which channel to transmit. For models in which the transmitter must transmit over the probed channel, it has been shown that a myopic policy probing the channel most likely to be ON is optimal. In our work, we allow the transmitter to select a channel over which to transmit that is potentially different from the probed channel. For a system of two channels, we show that the choice of which channel to probe does not affect the throughput. For a system with many channels, we show that a probing policy that probes the channel that is second most likely to be ON results in higher throughput. We extend the channel probing problem to dynamically choose when to probe based on probing history, and characterize the optimal probing policy for various scenarios.

7)A Framework for Real-Time Communication over Unreliable Wireless Channels:
We have developed a framework
for wireless networks with unreliable channels to clients, requiring a minimum timely-throughput of packets with hard per-packet deadlines
in order for a packet to be useful. We have also shown that
scheduling policies based on ,"debt" called
maximum debt first policies (MDF), are timely-throughput optimal.
By this we mean the MDF fulfills any set of client requirements
for which there exists a policy that
fulfills them. The debt of a user is the difference
between the required delivery ratio and the actual throughput
of packets that have been delivered to that client.
The maximum debt first (MDF) serves the clients in
decreasing order of debts at the beginning of every frame.

However, the notion of timely-throughput optimality is a very weak notion
of optimality. For example, it does not measure the fluctuations in the rate if delivery o packets over time.
Several delivery streams can have the same mean throughput, though some of
them could be significantly burstier than others.
As an example, the sequence of packet deliveries in each frame
(1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0,1,1,1,1,0,0,0,0,1,1,1,1 ...)
has the same throughput 1/2 as the sequence (1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0, ...),
though it is significantly burstier.
That is, there could long intervals of time in which there are no packet deliveries.
Motivated by this we have developed an analysis of the fluctuations in packet deliveries.
We employ a law of the iterated logarithm (LIL) scaling and determine an upper bound on the
running cumulative number of timely-packet deliveries normalized by a LIL scaling
that is touched infinitely, characterizing the fluctuations. We are addressing the problem of timely delivery of packets in sensor networks and wireless networks.
In previous we have analyzed wireless networks
where clients served by an access point require a timely throughput
of packets to be delivered by hard per-packet
deadlines and also proved the timely-throughput optimality
of certain debt-based policies.

8)Dynamics of a Simple Rational Planar Map
We completed our investigation of the relation to chaotic systems on the dynamics of a 2-D rational map for various values of its control parameters. Despite its simple structure this map is very rich in nonlinear phenomena such as, multi-scroll strange attractors, transitions to chaos via period doubling bifurcations, quasi-periodicity as well as intermittency, interior crisis, hyper-chaos etc. In our work, strange attractors, bifurcation diagrams, periodic windows, invariant characteristics
were investigated both analytically and numerically.

9) Coordinated Scheduling and Power Control for Downlink Cross-tier Interference Mitigation in Heterogeneous Cellular Networks
Heterogeneous cellular networks are multi-scale networks that are becoming widely deployed. In heterogeneous cellular

networks, the deployment of low-powered picocells provides user offloading and capacity enhancement. The expansion of a picocell's coverage by adding a positive bias for cell association can maximize these effects. Under this circumstance, downlink cross-tier interference from a macro base station to pico mobile stations in the expanded picocell range deteriorates those pico mobile stations' performance significantly. In a new direction of research,
we developed a coordinated scheduling and power control algorithm, whereby the macro base station reduces its transmission power for those victim pico mobile stations in the expanded picocell range only on a set of resource blocks to minimize performance degradation at the macro base station. First, the transmission power level is calculated based on the mobile stations' channel condition and QoS requirements. Then, a set of resource blocks is determined by solving a binary integer programming to minimize the sum of transmission power reduction subject to victim pico mobile stations' QoS constraints. To reduce computational complexity, we utilized a heuristic algorithm, i.e., max-min greedy method, to solve the problem. Through system level simulations, we showed that the average and 5%-ile throughputs of victim pico mobile stations are significantly improved.

Area 3 - Network Inference and Information Assurance in Multi-scale Networks

(1) Inference Models for Multi-scale Networks with LRD Traffics
We completed our investigation of the effects of LRD phenomena on the detection against important attacks on MANET Protocols. We focused our investigations on the OLSR (and similar) routing protocols; specifically wormhole attacks. Our investigations included detection of the attacks as well as mechanisms, including network architectures that render them not effective in various MANETs. We investigated sequential detection formalisms using quickest change detection algorithms, parametric and non-parametric, as well as topology effects, and showed, using our results from Area 1 (Traffic Modeling and Performance Analysis for Multi-scale Networks), that LRD phenomena deteriorate the performance of detectors of these attacks. In our work, we developed an anomaly detection scheme based on multi-scale analysis of the long range dependent traffic to address this challenge. In our detection scheme, the discrete wavelet transform is used to approximately decorrelate the traffic data and capture data characteristics at different time scales. The remaining dependencies are then captured by a multi-level hidden Markov model in the wavelet domain. To estimate the model parameters, we developed an online discounting Expectation Maximization (EM) algorithm, which also tracks variations of the estimated models over time. Network anomalies are detected as abrupt changes in the tracked
model variation scores. Statistical properties of our detection scheme were evaluated numerically using long range dependent time series. We also evaluated our detection scheme in malicious scenarios simulated using the NS-2 network simulator.

2) Network Sampling

Network sampling is at the heart and foundation of our understanding of many networks. In recent work, we have developed a framework that outlines the complete spectrum of computational models for network sampling and we have explored methods of sampling that generalize across the spectrum going from the easiest and least constrained model of static graphs to the more difficult and realistic model of sampling from graph streams. We extended traditional sampling algorithms from each of the three classes of sampling methods (node, edge, and topology) for use on graph streams. Besides showing how traditional sampling algorithms can be modified for use on graph streams, we also define a family of graph-based induction algorithms that generalize across the full spectrum of network sampling models (from static to streaming) while efficiently preserving most of the graph properties for streaming and static graphs. Interestingly, our family of algorithms, while less complex are shown to preserve the graph properties of static graphs even better than the more complex algorithms (such as breadth-first search) that do not generalize to the streaming graph model.

(3) Embedding capacity
We obtained a characterization of embedding capacity provided by a pair of independent renewal processes. We showed that the embedding capacity can be computed via the inversion of a structured linear system that, for a broad range of renewal models, admits a fully analytical expression in terms of the renewal function. This result enables us to explore properties of embedding capacity, obtaining closed-form solutions for selected distribution families and establishing an order for selected classes of distributions.

4) Detection of SSH Keystroke Packets in TCP Connections
A streaming algorithm detects SSH client keystroke packets in any TCP connection. Input data are timestamps and TCP-IP header fields of packets in both directions, measured at a monitor on the path between the hosts. The algorithm uses the

packet dynamics just preceding and following a client packet with data to classify the packet as a keystroke or non-keystroke. The dynamics are described by classification variables derived from the arrival timestamps and the packet data sizes, sequence numbers, acknowledgment numbers, and flags. The algorithm succeeds because a keystroke creates an identifiable dynamical pattern. One application is identification of any TCP connection as an SSH interactive session, allowing detection of backdoor SSH servers. More generally, the algorithm demonstrates the potential for the use of detailed packet dynamics to classify connections. This is the first algorithm for detecting SSH keystroke packets in a connection on any port. The first application in security monitoring is to detect backdoor interactive SSH logins. Because the algorithm is streaming, its implementation can scale to the gateway of a very large inside network. The algorithm was implemented in the widely-used Argus system and was made available in the
last release.

5) Nonparametric and unsupervised detection of information flow
Under this topic, our research focused on two aspects: (i) the characterization of fundamental limits on the maximum undetectable information flow for general renewal processes; (ii) developing effective intrusion detection schemes for time varying traffic models. The second aspect is described in detail below:
The main result is threefold: the development of a nonparametric flow detection algorithm for unidirectional or bidirectional flows, the related performance analysis, and experiments with synthetic and real data. In developing an algorithm, our main contribution is a new nonparametric technique that does not rely on knowledge of traffic distribution; nor does it require a training data for either hypothesis. In algorithm analysis, we establish the consistency property of the proposed detector for a class of non-homogeneous Poisson traffic. The performance of our detector is evaluated using synthetic Poisson traffic, LBNL TCP traces and real-world measurements from MSN VoIP sessions, and comparison with other passive detectors is provided. The use of synthetic data allows us to examine the trade- offs between miss detection and false alarm probabilities using Monte Carlo simulations. LBNL TCP traces and MSN VoIP traces are of course not guaranteed to satisfy the assumptions made in our algorithm analysis, and our results indicate a level of robustness.

Conclusions
During the project duration, we have made significant progress towards our goal of developing the theoretical foundations for modeling, analysis, and control of multi-scale military networks. In particular, we developed an understanding of the causes of multi-scale phenomenon including long-range dependence (LRD) in wireless systems, and how to model them in the presence of fading channels and spatial-temporal correlations. We made significant progress in our investigation of the impact of wireless network protocols on traffic characteristics, in terms of traffic burstiness, self-similarity and long range dependence. We have developed tools for controlling multi-scale network traffic that go beyond the traditional realms of throughput maximization and stability, and begin to uncover the impact of delay on such systems. We investigated the impact of LRD traffic on network control with focus on multi-scale decompositions. We also developed a unifying framework for designing low-complexity scheduling policies in the downlink of multi-channel (e.g., OFDM-based) wireless networks that can provide optimal performance in terms of both throughput and delay. Finally, we developed traffic models that incorporate timing information in network systems for inference and information assurance. Based on the characterization of flow detectability, we designed low-complexity detection systems for security attacks, user behaviors, and social connectivity, and investigated the development of distributed systems with local information.

Technology Transfer